TAGUCHI DESIGN ANALYSIS FOR INFLUENCE OF VARIOUS FORMING PARAMETERS INTERACTION OCCURS IN INCREMENTAL FORMING

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Incremental Forming, IF is a sheet forming process based on layered manufacturing principles. The finished product is achieved by the CNC machine. The commercial finite element code ANSYS v.11.0 is used for studying the SPIF process under definite procedure conditions. The paper presents the Taguchi Design analysis and main results of a study of interaction effects between five various forming parameters at five levels on SPIF through FEA. The reduction of Taguchi's quality variation was attempted through experiments based on the certain selection of S/N ratio and parameter levels. The simulation modeling predicted a design with reasonable results that recommend the Taguchi technique as a prediction method.

Keywords: incremental forming, finite element analysis, Taguchi's methodology, Signal-to-Noise ratio

1. Introduction

Incremental Forming, IF can be successfully used for producing prototypes or small volumes [1]. It is a highly flexible process used for forming metal sheets. It is possible to form sheet metal products without specific dies [2]. The forming tool moves along a series of contour lines at a constant path increment in vertical depth direction and gradually deforms the blank into the desired product profile. The tool path is edited and programmed by Computer-Aided Manufacturing, CAM software and then produced using a Computer Numerical Control, CNC milling machine [3]. One cycle of the IF operation is illustrated in Fig. 1.

However, the IF process presents some drawbacks; it makes forming time longer compared to conventional Deep Drawing process. It is limited to small size production batches, springback occurs, and the process generates less geometry accuracy, particularly in convex radius and bending edges areas [4]. The quality and the accuracy of the surface are mainly influenced by the spindle speed (ω), tool diameter (D_p), tool vertical step size (Δz) and feed rate (v). It is possible to obtain satisfactory products by selecting suitable values for these parameters and by improving the trajectory of the forming tool path [5].

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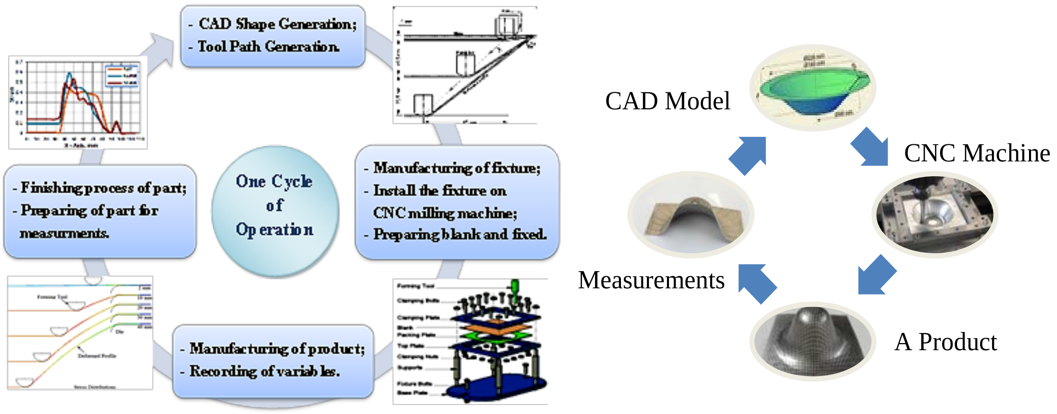

Fig. 1. Incremental forming representative illustration

In order to analyze the forming parameters effects on the formability of materials, a component with circular generatrix and wall angles variable to the depth was examined. The interactions between step size and tool size or tool size and feed rate have significant effects in the polymer formability [6]. Through incremental forming, the results of maximum wall angle, feed rate, spindle speed, step size, and tool size indicate that the highest effect has the 57% step size [7].

The influence of tool diameter, step size and friction coefficient on the springback, forming force and thickness distribution was analyzed [8]. It is found that the genetic algorithm is a suitable tool for the optimization of process factors to minimize springback values and vertical force and maximize the minimum thickness of the sheet.

The effects on the quality of the surface, step size, feed rate, tool diameter, and spindle speed were analyzed based on surface roughness and macrostructure. All these parameters influence the quality of the surface [9]. The main contribution to predicting and optimizing the wall angle and the surface roughness were studied. It is concluded that the lubricant has the highest positive impact on wall angle [10].

The minimum percentage of thinning as design criteria was applied in the Taguchi method and verified through the FE model using the optimum die design [11]. The predicted Taguchi response was within 5.9% from FE analysis prediction.

In this paper, the formability of the material and the higher parameters effect during the Single Point Incremental Forming (SPIF) deformation is studied. The conical profiles of AL AA1025 alloy are tested using Finite Element Method (FEM). The experiments design for this purpose is executed through Taguchi's Methodology (TM). The SPIF process parameters were five variables: blank thickness, friction coefficient, forming tool diameter, step size and feed rate with five levels for each.

2. Taguchi's Methodology

2.1 Taguchi experimental design approach

Taguchi's Methodology (TM) has been widely employed recently in several industrial and research fields. By applying the TM technique, the time required for experimental studies can be significantly reduced. The method is very efficient in analyzing the impact of various factors on the performance of the system [12, 13].

The Taguchi's methodology uses orthogonal arrays for the evaluation of the factors influence on the response mean and variation [14]. The Taguchi approach introduces the design of the experiments in support of:
i) design the processes resistant to environmental conditions; ii) design and development of the products; as well as the processes resistant to component differences; iii) reducing deviation around the important target value.

2.2 Taguchi technique philosophy

The development of the Taguchi design involves three stages [15, 16]:

- System design; the procedure of applying engineering and scientific information for creating a design of the basic functional pattern;
- Parameter design; the procedure leads to recognizing the design parameters sets that improve the performance characteristics and decrease the sensitivity of industrial processes design to noise variation. Parameter design involves several forms of testing in order to evaluate the noise factors effect on the product performance characteristics, which is defined by a specified set of values. This testing aims to choose the best levels for the governable design parameter;
- Tolerance design; the procedure of determining the tolerances around the nominal situation recognized in the process of the parameter design.

In addition, TM has presented three essential concepts for the public design:
I. Minimize the loss in the quality, a deviation function of the performance variables from wanted values;
II. Reduce the environmental and industrial deviations in the design of the products;
III. By using the partial factorial Orthogonal Arrays (OAs) in order to run tests, a process borrowed from the design of the traditional experimental [15].

2.3 Signal-to-Noise ratio

There are several recommended Taguchi forms into which investigational data on the performance of the process could be converted before optimization. Taguchi named these special forms the Signal-to-Noise, S/N ratios. S/N ratio represents a type of data which is capable of collecting two physical characteristics into the chosen one. It is used in evaluating the statistics for parameter strategy.

The maximum S/N ratio corresponds to minimum loss. The robustness objective setting is also determined with the use of S/N ratio. The purpose of the S/N ratio is to be at the maximum value for design optimization [12, 15].

Experiments of the Taguchi design were arranged in twenty-five tests, with three reproductions for each test. In order to reduce the time and the resources needed for generating the tests, a 5-level design is presented, as shown in Table 1.

Table 1

Design of variation levels and design of simulation models

Variables	Levels of Variation				
	X_{-2} -2	X_{-1} -1	X_0 0	X_1 +1	X_2 +2
t_{in}, mm	0.4	1.0	1.45	1.9	2.5
μ	0.07	0.11	0.14	0.17	0.21
r_{tool}, mm	5.0	6.5	7.5	8.5	10.0
Δz, mm	0.2	0.6	0.85	1.1	1.5
v, mm/min	1000	4000	6000	8000	11000

Test no.	t_{in}, mm	μ	r_{tool}, mm	Δz, mm	v, mm/min
1	-2	-2	-2	-2	-2
2	-2	-1	-1	-1	-1
3	-2	0	0	0	0
4	-2	+1	+1	+1	+1
↓	↓	↓	↓	↓	↓
22	+2	-1	-2	+2	+1
23	+2	0	-1	-2	+2
24	+2	+1	0	-1	-2
25	+2	+2	+1	0	-1

The aim of this research is to evaluate which forming variables affect the formability of material in SPIF process by FEM. TM technique is used to understand the relating effects. Five forming variables were considered: i) blank thickness mm, t_{in}, ii) friction coefficient, μ, iii) tool radius mm, r_{tool}, iv) step size mm, Δz and v) feed rate mm/min, v. Levels of variation parameters are shown in Table 1. The responses of the tests at stroke end (complete product) were maximum stress $\sigma_{eq.}$, maximum strain $\varepsilon_{eq.}$, depth of maximum deformation y_{max}, final thickness t_f and thinning percentage th.%.

3. Development of FE simulation model

The FE model simulation covers the impact of the elastic-plastic material behavior. Additionally, the simulation was enhanced by applying various variables with constant values for the blank and fixture (materials and dimensions).

The effects of the tools and supporting die loads on the blanks are shown in Fig. 2. Table 2 presents the initial data of the Al AA1050 used in this work. The finite elements with 2-D modeling were chosen:

• For the blank material, the element VISCO106-four nodes was selected, with 2 DOFs/node: translations in the nodal X and Y directions;

• For the forming tool and the fixture (blank holder and die), the element PLANE42-four nodes used with 2 DOFs/node: translations in the nodal X and Y directions [17]. The type of mesh that represents the blank material is a quadrilateral mapped mesh.

The boundary conditions illustrated in Fig. 2 are:

a. Constrain the blank center in X-direction, displacement equal to zero;
b. Constrain the die tool in directions X and Y, displacement equal to zero;
c. The blank holder was constrained, movement in Y-direction only;

d. Constrain the forming tool to follow the designed tool path by CAD codes and the feed rate represented as angular velocity;
e. The fundamental conditions of the tool set include: forming tool movement is at a 45°, the maximum depth is 40 mm, the tool location is constrained at 80 mm from the blank center, and the die edge radius is constant, *R*=5 mm, (Fig. 2).

Three contact interfaces were defined:
i. the blank-lower surface // the die, ii. the blank-upper surface // the forming tool, and iii. the blank-upper surface // the blank holder.
Rigid-to-flexible behavior contacts are represented by the 2D elements, TARGE169 and CONTA171 of the pair Point-to-Surface. There are two DOFs/node allowed for these elements: translations in the nodal X and Y directions [17].

Table 2

Initial data

Variable	Density, ρ (g/m^3)	Young's modulus, E (GPa)	Poisson's ratio, ν	Yield stress, σ_Y (MPa)	Tangent modules, Eτ (GPa)
Value	2700	75	0.3	80	0.5

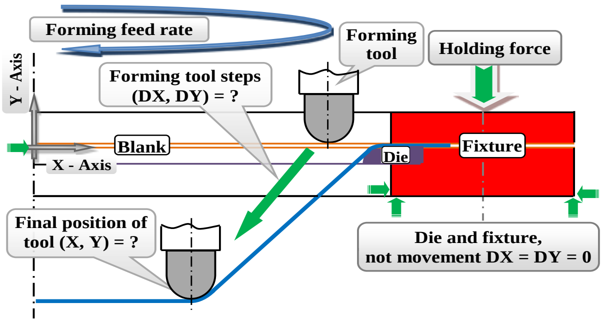

Fig. 2. Boundary conditions in the SPIF process and expected profile

The non-linear analysis employed includes incremental load, convergence criteria and specified load steps. The minimization of the force residual was used for the convergence tolerance; the default tolerance in ANSYS is 0.1%. The analysis included consecutive SPIF process steps for tool stroke differences [18].

4. Results and discussion

All effects of forming parameters and their interactions are illustrated graphically and classified into:
a- individual relationships, the effect of a parameter value variation on a response;
b- interaction relationships between two parameters values variation on a response;
c- interaction relationships between all parameters values variation.

In classical designed experiments, the primary goal is to identify parameters that affect the mean response and control them to desirable levels. Taguchi design focuses on reducing variability, as well as setting the mean to target. The main effects of the forming parameters for frustum shape, 45^o wall angle, 40 mm high, constant forming tool path and their interactions are described in Fig. 3.

The relationships built on the effect of one parameter with fixed other parameters, as well as a limit that the effects by one response are called traditional relationships, either direct or indirect proportional. According to these relationships, increasing tool radius caused decreasing the surface finish of the blank [19].

4.1. Final thickness, strain and stress distributions

Thickness distribution and strain localized field across the formed part are necessary to any intermediate formability evaluation. Fig. 3-a represents the thickness distributions when the part is completely drawn for the tests (1 to 5) (Table 3). It shows the effect of four parameters (increase) with fixed blank thickness (0.4 mm). The thickness decreased with high irregularity in the test no. 2. The thinning values were reasonable at the region between 0 to 40 mm distance from the center of the part, and the thinning percentage was 25%. The blank thinning is concentrated under the direct contact, tool-blank. Therefore, it is difficult to evaluate this relation and to establish which parameter has more effect.

Strain distribution results represent the strain value for each node in the numerical model of SPIF and also the strain values of all nodes at each step size of the forming tool. Fig. 3-b represents the strain distribution at the upper surface of the formed part. At the same levels and parameters condition, there is no clear behavior indicating the effects of the parameters. There are regular strain distributions at the region between 0 to 40 mm distance from the center of the part.

In general, the effects concentrate between 40 to 90 mm distance from the center of the part and 26 to 40 mm depth and they decrease towards the part's center.

The maximum strain values are concentrated on the contact places between the forming tool and blank surface. No forming operation occurs under the blank holder and the strain distribution is more uniform.

Studying the simulation model results included the analysis of all forming stages depending upon the step size of each experiment. An example of these stages is shown in Fig. 3-c, in-depth 2, 10, 20, 30 and 40 mm.

The figure shows the contact statuses between the product and the tool. The contact area increases with increasing of the forming depth and more circumvolution of the formed part appears around the forming tool profile with increasing of forming depth. Any appearance of high stress values along the deformed blank section predicts critical boundary conditions and failure. Stress distribution values increase with the forming depth until the maximum value 252 MPa at 40 mm depth and at the regions with maximum thinning (Fig. 3-c).

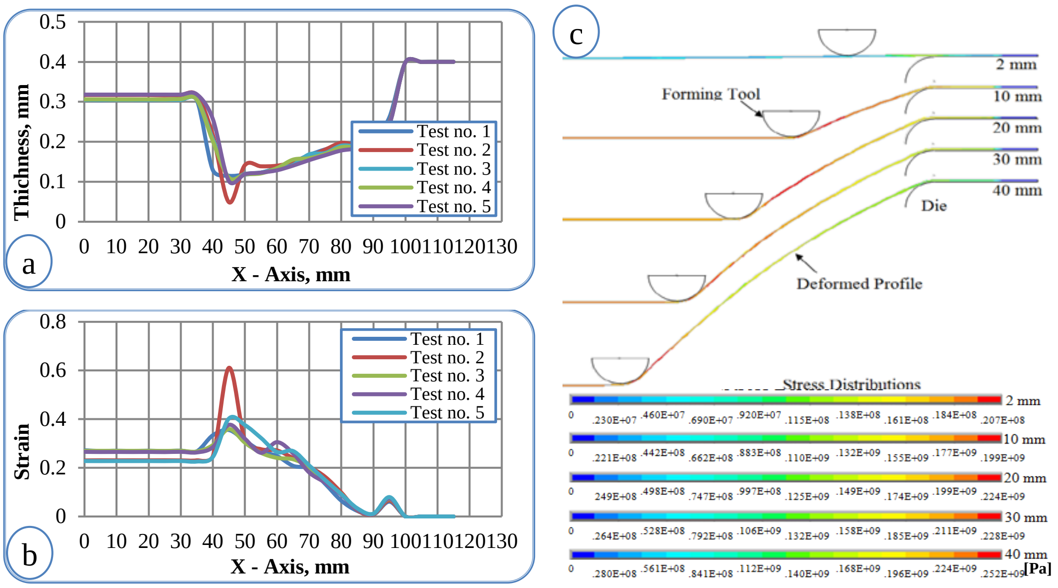

Fig. 3. Final thickness, strain and stress distribution of blanks with thickness 0.4 mm

The result of the simulation processes in this SPIF model is based on the mean value of each process parameter variable. Table 3 shows the results (stress, strain, maximum depth of maximum strain, final thickness and thinning percentage) of 25 tests based on the Taguchi method, as well as the parameters studied.

Table 3

Results of FEM simulation models

Test no.	t_{in}, mm	μ	r_{tool}, mm	Δz, mm	v, mm/min	σ_{eq}, N/m^2	$\varepsilon_{eq.}$	y_{max}, mm	t_f, mm	*th*.%
1	0.4	0.07	5.0	0.20	1000	2.523e8	0.387	-36.6	0.346	13.33
2	0.4	0.11	6.5	0.60	4000	2.65e8	0.601	-34.0	0.230	42.45
3	0.4	0.14	7.5	0.85	6000	2.56e8	0.369	-35.4	0.304	23.97
4	0.4	0.17	8.5	1.10	8000	2.63e8	0.394	-37.1	0.282	29.29
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22	2.5	0.11	5.0	1.50	8000	2.94e8	0.589	-5.52	1.689	32.41
23	2.5	0.14	6.5	0.20	11000	3.42e8	0.688	-9.83	1.451	41.93
24	2.5	0.17	7.5	0.60	1000	2.97e8	0.815	-6.50	1.298	48.08
25	2.5	0.21	8.5	0.85	4000	3.08e8	0.849	-5.53	1.185	52.59

TM provides the orthogonal array as a mathematical tool that allows, with the use of a reduced number of experiment runs, analyzing the relationship between a large number of design parameters. The target of TM is based on the conditions identified for the optimal process or product performance. Taguchi uses the S/N ratio as a support for quality assessment in tests applying an orthogonal array design. The trial result data is converted through the S/N ratio into a value for the evaluation characteristics as the optimum setting analysis.

4.2. Signal-to-Noise ratio response

The plot of response value average for every level is the most influential plot of the process variables or design parameter. The sign of the main effect indicates the direction of the effect, whether the average response value increases or decreases. The magnitude indicates the strength of the effect. If the effect of a process parameter is positive, it implies that the average response is higher at a high level than at a low level of the parameter setting. In contrast, if the effect is negative, it means that the average response at the low-level setting of the parameter is more significant than at high level.

The maximum stress against the output is to analyze and determine which are the optimal parameter factors for the SPIF process. The reject should be in maximum as the unacceptable of the result. In the present study, the "smaller-the-better" quality principle is applied in the selection of the Signal-to-Noise ratio.

a. S/N ratio, main effect plot

Fig. 4 includes the graphical representations of the simulations for the S/N ratio of the process. A lower S/N ratio signifies higher quality. The least significant parameter is the feed rate, followed by the step size and friction coefficient. The parameters with the higher influence are blank thickness and tool radius. For blank thickness, it decreases slightly from -2 until +1 level and increases, approaching the mean line for the level +2 blank thickness.

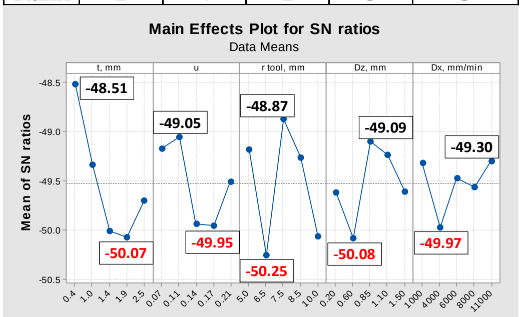
The friction coefficient increases from -2 to -1. The S/N ratio is constant at levels between -1 and 0. The ratio decreases at level +1, approaching the ratio mean value. Regarding the tool radius, between levels -2 and -1, the ratio has decreased, approaching the minimum value. This evolution was then followed by an increase of the tool radius until -1 and 0, decreasing until +2. The curve behavior of step size parameter was similar to the tool radius curve, but with less S/N ratio values. When the feed rate is analyzed, the decrease of the S/N ratio reaches to the level -1 from -2, approaching the mean S/N ratio, and then decreases close to the mean S/N ratio to the level +1, followed by an increase to the level +2.

As described by the values in the Fig. 4 table, the main parameters influencing the stress in the SPIF process are tool radius and blank thickness. These two parameters are the most significant and can be used as control factors. Step size and friction coefficient have less impact and feed rate is the least significant factor.

The results of the five-level simulation for each factor are presented in Fig. 4, with a focus on the S/N ratio impact. In terms of blank thickness, the values of the S/N ratio are -48.51 for level 1, -49.33 for level 2, -50.01 for level 3, -50.07 for level 4 and -49.69 for level 5, which makes level 4 the best choice for blank thickness in order to obtain the lowest S/N ratio average. The values of the S/N ratio for 1 to 5 μ (friction coefficient) levels are: -49.17, -49.05, -49.94, -49.95 and -49.51. The best value for the S/N ratio for μ is recorded for level 4. The lowest S/N ratio is obtained at level 2, which recommends this level as the best option. The lowest value of the S/N ratio is the selection criteria for the parameter level, thus for tool radius, level 2 is chosen (-50.25). Level 2 is also chosen for step size (-50.08) and for feed rate (-49.97).

The selection of the parameters for obtaining the best quality of SPIF simulation indicates the following ratio (Fig. 4): $t_{in}4$ $\mu 4$ $r_{tool}2$ $\Delta z2$ $v2$.

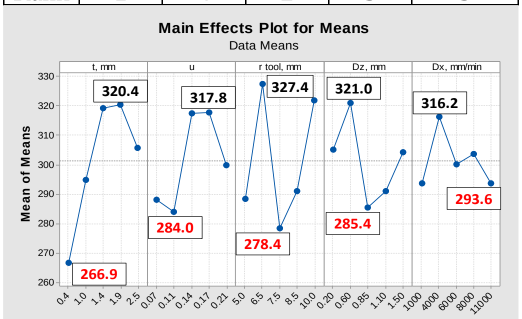
	t_{in}, mm	μ	r_{tool}, mm	Δz, mm	v, mm/min
Delta	1.56	0.90	1.38	0.98	0.68
Rank	1	4	2	3	5



Levels, 1, 2, 3, 4, 5

Fig. 4. S/N ratios response, smaller is better

	t_{in}, mm	μ	r_{tool}, mm	Δz, mm	v, mm/min
Delta	53.5	33.8	49.0	35.6	22.6
Rank	1	4	2	3	5



Levels, 1, 2, 3, 4, 5

Fig. 5. The means response

The range of S/N ratio variance resulted from the level setting; the change value equals to S/N ratio maximum – S/N ratio minimum. The impact of the parameter is higher when the range is larger. The ranking of the S/N ratio of the blank thickness is 1, and for the tool radius is 2, as indicated in the Fig. 4. These rankings demonstrate the strong influence on the stress level.

The ranking of the S/N ratio of the step size is 3, for the friction coefficient is 4, and for feed rate is 5. Therefore, the values of the S/N ratios of the blank thickness and tool radius need to be controlled in order to reduce the stress of the product during the SPIF process. The parameter with the highest impact on the end-product is the control factor toward blank thickness and tool radius, as illustrated in the table from Fig. 4. The other parameters, such as friction coefficient, feed rate and step size do not influence the output to the same extent.

b. The means, main effect plot

Fig. 5 presents the maximum stress values used to assess the effect of parameters on the SPIF process. The most suitable values for each parameter for obtaining the best product are also indicated. Feed rate is the less significant parameter, as opposed to the other parameters. It is followed by both friction coefficient and step size, while the blank thickness and tool radius parameters were more significant. The minimum mean value was at level -2 of the blank thickness parameter, while the maximum value was at level -1 of the tool radius parameter. For the feed rate, the mean is increased from level -2 to level -1. It decreased afterwards, near the mean line for 0 and +1 levels. This was followed by a decrease to +2 level. The thickness of the blank begins with a slight increase in the diagram, between level -2 and +1 then decreased toward the mean.

The mean of the tool radius increases steadily between -2 and -1, reaching the mean maximum. The increase is then followed by a decrease for level 0, and return to increase for levels +1 and +2. The mean value of friction coefficient, μ decreased from level -2 to level -1, and then increased to level 0. But between level 0 and +1 the mean value almost didn't change, and decreased to level +2. The step size parameter mean value had an exact opposite behavior than of the friction coefficient.

The Fig. 5 illustrate the fact that the most important parameter influencing the result of the SPIF process is the blank thickness, which is also the control factor, followed by the tool radius. The friction coefficient and step size have less impact than the first two parameters. The impact of each parameter on the mean is shown in the Fig. 5. The values resulted after applying five levels of settings for each parameter are included in this table. The mean value of blank thickness at level 1 is 266.9, at level 2 is 295.0, at level 3 is 319.2, at level 4 is 320.4 and at level 5 is 305.8. The lowest average mean level is recorded at blank thickness level 1, which becomes the best option. The mean values of the friction coefficient are 288.3 at level 1, 284.0 at level 2, 317.4 at level 3, 317.8 at level 4, 299.8 at level 5. The best option for the friction coefficient is level 2. For the tool radius and step size parameters, the level with the lowest mean value is level 3, and for the feed rate parameter is level 5. Improved stress value of the SPIF simulation can be obtained by using the parameters ratio $t_{in}1$ $\mu 2$ $r_{tool}3$ $\Delta z 3$ $v5$, according to the above analysis.

The range of mean-variance caused by level setting modification equals the mean maximum – mean minimum value. Therefore, the larger the range, the more significant the impact of the control factor on stress distributions is.

According to the ranking included in the table in Fig. 5, 1 and 2 rankings belong to blank thickness and tool radius, which indicate a relatively significant influence of these parameters on the product quality. Thus, step size and friction coefficient are the ranking 3 and 4 as they have relatively weak impacts, followed it the weakest ranking 5, feed rate parameter.

An abstract of the effect of the parameters upon the responses by evaluation of the S/N ratio and the means are shown in Table 4. The evaluation of the stress, strain and thinning percentage is based on the “smallest is the best” principle, while the maximum depth of maximum strain and the final thickness are based on the “largest is the best” principle.

The average of both S/N ratio and the means are indicated, showing the powerful impact and the control factor for each parameter studied. Based on these results, the type of the evaluation (powerful impact or control factor) and type of these required responses present the optimum relationship between the studied parameters.

Table 4

S/N ratio average and means average

Taguchi analysis: $\sigma_{eq.}$, Smaller is Better						
	Parameter	t_{in}, mm	μ	r_{tool}, mm	Δz, mm	v, mm
S/N ratios	Min	-50.07	-49.95	-50.25	-50.08	-49.97
	Level	4	4	2	2	2
	Delta	1.56	0.90	1.38	0.98	0.68
	Rank	1	4	2	3	5
	Optimize	$t_{in}4\ \mu4\ r_{tool}2\ \Delta z2\ v2$				
The means	Min	266.9	284	278.4	285.4	293.6
	Level	1	2	3	3	5
	Delta	53.5	33.8	49.0	35.6	22.6
	Rank	1	4	2	3	5
	Optimize	$t_{in}1\ \mu2\ r_{tool}3\ \Delta z3\ \boldsymbol{v}5$				

Taguchi analysis: $\varepsilon_{eq.}$, Smaller is Better		
S/N ratios	Optimize	$t_{in}3\ \mu4\ r_{tool}5\ \Delta z1\ v2$
The means	Optimize	$t_{in}1\ \mu1\ r_{tool}1\ \Delta z5\ v1$
Taguchi Analysis: y_{max}, Larger is Better		
S/N ratios	Optimize	$t_{in}1\ \mu3\ r_{tool}2\ \Delta z5\ v1$
The means	Optimize	$t_{in}1\ \mu3\ r_{tool}2\ \Delta z4\ v1$
Taguchi Analysis: t_f, Larger is Better		
S/N ratios	Optimize	$t_{in}5\ \mu1\ r_{tool}1\ \Delta z5\ v1$
The means	Optimize	$t_{in}5\ \mu2\ r_{tool}1\ \Delta z5\ v4$
Taguchi Analysis: *th*.%, Smaller is Better		
S/N ratios	Optimize	$t_{in}3\ \mu4\ r_{tool}5\ \Delta z2\ v2$
The means	Optimize	$t_{in}1\ \mu1\ r_{tool}1\ \Delta z5\ v3$

5. Conclusions

The Taguchi method is an effective and organized mechanism that enables the optimization of the design parameters. The method is based on a few experimental series that establish the fundamental factors with impact on the process.

The design of experiments is developed as a preliminary illustration of the Single Point Incremental Forming process. The effects of the forming parameters and their interdependencies predict the impact of the parameters on formability.

The ranking of the S/N ratio of the blank thickness and of the tool radius demonstrates the strong influence on the stress level. Therefore, the values of the S/N ratios need to be controlled in order to reduce the stresses during the SPIF process.

According to the ranking of the means-variance, the blank thickness and tool radius indicate a significant influence of these parameters on the product quality. Thus, step size, friction coefficient and feed rate have a relatively weak impact.

The calculated S/N ratios and the mean values from the simulation modeling predicted a design with reasonable results that recommend the Taguchi technique as a solid optimization and prediction method.

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